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MANUPLAN

A Precursor to Simulation for Complex Manufacturing Systems

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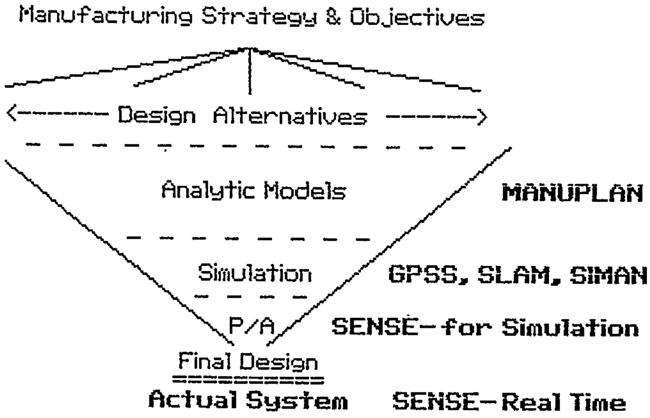
ABSTRACT

MANUPLAN is a tool for designing and analyzing manufacturing systems. In the early stages of manufacturing systems planning, it offers an efficient alternative to simulation modelling. MANUPLAN is based on a state-of-the-art analytical model. It is practical and easy to use, being simpler and quicker than simulation models. In a typical case, a system design that would have taken several weeks to evaluate using simulation was evaluated in under two days with MANUPLAN. Inputs to MANUPLAN are the basic system design data: information on part routing, equipment capacities and reliabilities, and production requirements. Outputs from MANUPLAN include part flow times, work-in-process levels, equipment utilizations, and production rates achieved. Each run by MANUPLAN takes only a few seconds. By changing the system design data, manufacturing designers can quickly understand the trade-offs between inventory levels, production requirements, flow times, and equipment reliabilites, for their system.

1. INTRODUCTION

1.1 The System Design Process

MANUPLAN is a software tool to assist in the planning and design of manufacturing systems. The best way to understand the role of MANUPLAN is to look at the manufacturing system design process.[1,2]



At an early stage of manufacturing system design and planning, designers need a tool that allows a wide range of models to be set up and explored quickly. MANUPLAN fulfills this function. It narrows the candidate systems down to a few alternatives for detailed simulation, which can then be performed using well-known languages such as GPSS/H.[3] After that, planners can use perturbation analysis (P/A) [4,5] implemented in programs such as SENSE [6] for fine-tuning simulations and also for improving operation of the actual manufacturing plant.

Simulation models allow the study of detailed inter-actions of components and allow the manager to make detailed decisions about the system and then judge the impact of those decisions; simulations can be made extremely accurate and life-like.

There are, however, numerous disadvantages to running simulation models, especially in the early stages of planning. Simulation models require an enormous amount of detail; the requisite investment in labor and computer time, both to create the model and to keep it current, is large. Potentially even more costly, in the long run, is the limit that the tedium and rigidity of current simulation techniques put on the designer's creativity and willingness to experiment. It is precisely to overcome these disadvantages that an analytic model such as MANUPLAN is recommended for initial design.

1.2 MANUPLAN and Manufacturing Strategy

Why should system designers consider using MANUPLAN? In three words, the answer is: aggressive manufacturing strategy. To remain competitive and gain the edge in efficiency, managers and designers need to study as many design alternatives, in as short a time, as possible. MANUPLAN is an analytic model which allows managers to bridge the gap between their manufacturing strategy and expensive simulation leading to final system design. MANUPLAN should be used to determine which design alternatives are worth simulating. MANUPLAN's modest data requirements and evaluative reports actually enhance a designer's ability and creativity.

Briefly, the advantages of MANUPLAN are:

* easy analysis of "first-cut" designs
* alternate scenarios are quickly compared
* modest data requirements (quick setup)
* inexpensive to acquire and operate

1.3 Overview of MANUPLAN

MANUPLAN is based on a state of the art analytical model which combines network-of-queues and reliability modelling. Before a part in a system can be completed, it must visit several different processing centers. If a part encounters a busy station it must wait in a queue, possibly with other parts, before it can be processed. Thus, each part experiences a "network of queues" in its journey through the manufacturing system.

The processing time required for any particular operation is known from the part processing data. The mathematical model used in MANUPLAN estimates the dynamics of the interactions between the resources and the workpieces in the system, and hence the time that a workpiece spends waiting at each resource. From this, MANUPLAN can then predict the production rates, the utilization of equipment, and the average number of pieces waiting at each resource. An important feature of MANUPLAN is that it also takes into account the effects of equipment reliabilities (failures and repairs) on the operation of the system.

Briefly, inputs to MANUPLAN include:

* number of hours of operation per year
* for each equipment group
    number in group
    reliability measures (mttf & mttr)
    overtime factor
* part number
    annual demand
    lot size
    fixturing requirements
* routing data (for each part)
    operation name
    next operation(s)
    assignment to equipment group(s)

Additional data input items are described later.

Outputs from MANUPLAN include:

* production summary for each part type:
    production rate achieved
    quantity of scrap produced
    flow time through system
    average work-in-process inventory
* for each equipment group
    equipment utilization
    proportion of capacity required for:
        production
        repair
    work-in-process at the group

All of these aspects of MANUPLAN will be described in more detail below. First we provide some background to the techniques used in MANUPLAN.

2. BACKGROUND ON ANALYTIC MODELS

2.1 Static Models

The simplest analytic models used for evaluating manufacturing systems are static allocation models, also known as work-center loading models [1,2]. These models simply add up the total amount of work allotted to each resource, and compare that with its available time. Such models ignore all dynamics, interactions, and uncertainties in the system. They also cannot estimate the flow time of parts through the system. However, they do highlight the main bottlenecks, and due to their simplicity, they are often used for a very coarse evaluation of a system.

2.2 Dynamic Models

More sophisticated analytic models are provided by the theory of queueing networks. The improvements that this theory provides over the static models is that it allows us to model the dynamics, interactions, and uncertainties in the system, albeit in an aggregate way. In practice the arrival times of jobs to a work center are not precisely known, and also, the processing time may vary for different jobs. Some jobs may require two resources (e.g., a fixture and a machine) for an operation, others may require just one resource. These dynamic imbalances of flow rates and interactions between resources are not captured by the static models; however any manufacturing person appreciates the impact these can have on the performance of a system.

Models based on queueing network theory can estimate the effect of these factors on system performance. These models provide estimates of aggregate "steady state" performance -- in intuitive terms one can say they predict the average behavior of the system over a medium- to long-term time horizon. For instance, in a manufacturing system where operation times are of the order of 15 minutes to 4 hours, these models could be used to estimate performance over a period of 3 months or more. Typical performance measures available from these models are equipment utilizations, work-in-process (WIP) at each work center, and part flow times (see MANUPLAN outputs below for more details).

2.3 Accuracy of Analytic Models

Queueing network models are derived using many mathematical assumptions, and traditionally the manufacturing community has been concerned with the applicability of these models to their practical world. Recently, more and more researchers have been using the models (see references below), and have shown that quite reasonable estimates of performance are obtained. Typically, such models come within 5% to 15% of the values obtained from detailed simulation. More important, **the overall insight they provide about the system, and the decisions that result from these models, are appropriate for the design/planning stage.**

In addition, recent theoretical work by Suri [7] has shown that such models are surprisingly robust to changes in the underlying mathematical assumptions. Another analysis by Tay and Suri [8] shows that the models are also insensitive to errors in the part/equipment data. Both these analyses further justify the use of such models at the design/planning stage.

2.4 Limitations and Restrictions

Queueing network models are not appropriate, or may not be accurate, under certain situations. The model described here is not appropriate for short-term decisions (e.g., which operation should be done next). Nor is it appropriate for studying transient phenomena (e.g., how to best start up a facility that has been down for a long time). Also, queueing network models cease to be accurate when there is significant blocking in the system (when limited buffer space causes machines to stop operation because their output bins are full). The modelling of blocking has been the subject of considerable research -- for example see a bibliography of some 30 selected papers in the recent work of Suri and Diehl [9] . As yet however, an efficient and widely applicable solution techniqe has eluded researchers.

For these reasons it is important to repeat that MANUPLAN is highly appropriate as a precursor to simulation. It is the right tool for planning and preliminary design evaluation. However, we do not recommend finalizing a design or building a system without doing some detailed simulation. A good manufacturing design team should learn how to use MANUPLAN and simulation as complementary tools.

2.5 MANUPLAN and Other Analytic Models

The use of analytic models for performance evaluation of manufacturing systems has been advocated by several leading researchers: for example, see the works of Buzacott [10], Solberg [11], Stecke [12], and Suri and Hildebrant [13]. The work of these and other researchers has helped to make both the manufacturing and the modelling communities aware of the uses of analytic models for manufacturing systems.

However, it is also true that the analytic models cited above are still not being widely used by the manufacturing community. There are several reasons for this, which will become clear below. **Our main goal in developing MANUPLAN was to produce a software tool that would be easy to use, and oriented to the manufacturing community.** In order to achieve this goal, we developed the following features that are unique to MANUPLAN:

Manufacturing Terminology: All inputs and outputs of MANUPLAN are in common manufacturing vocabulary. Furthermore (unlike some other models that require an understanding of unusual parameters) MANUPLAN is driven by input parameters which are completely "natural" to a manufacturing system designer. By developing our input/output structure in this fashion, and by careful choice of how the inputs are to be specificed to MANUPLAN, we gained the next feature.

Easy to Learn and Use: In a typical case, an Industrial Engineer with a fresh Bachelors degree learned to use MANUPLAN in under half a day. She had made a preliminary evaluation of a proposed manufacturing facility in another half a day, and arrived at some important recommendations for the equipment designers. The project manager estimated that these recommendations reached his equipment designers a full two months earlier than if they had attempted to simulate the system as they conventionally had done in the past. It is clear that because of the ease with which MANUPLAN was learned and used, in this case the user had benefited from MANUPLAN within 48 hours of its installation!

High Efficiency: MANUPLAN is based on some new numerical methods that extend the state-of-the-art in analytic models of manufacturing (see Appendix). These methods enable large, complex systems to be analyzed extremely quickly and with comparatively low core-memory. For example, some installations of MANUPLAN allow 100 part-types and 200 work-centers to be modelled, on a typical medium-sized computer. Even with such large models, the time for MANUPLAN to evaluate the design remains between 1 and 10 seconds. This fast response is important for two reasons: i) it encourages greater exploration of designs, and ii) it allows the designer to maintain continuity of thought during such an exploration. By rapidly going over a number of trials with MANUPLAN, in just a few minutes the designer develops an intuitive "feel" for the trade offs between the parameters that are being manipulated. A series of trials can be carried through to conclusion before one is interrupted by a meeting or by a "lunch break"!

Numerical Stability: A problem encountered with previous analytic models has been that they occasionally fail to converge to a solution, or that they lose all accuracy under stressful cases. Great care has been taken in designing the numerical algorithms in MANUPLAN to shield the user from such problems. Each component of the solution package has been developed to be efficient for low stress cases, yet to retain its accuracy in high stress situations. Once again, our goal has been to allow those without expertise in numerical analysis to benefit from MANUPLAN; any manufacturing designer should be able to use MANUPLAN in his or her work.

Combines Network/Reliability Models: A novel and most useful feature of MANUPLAN is that it combines analytic queueing network models with analytic reliability models, into a new hybrid building-block (see Appendix). Equipment reliabilities are an important concern, particularly with the current emphasis on Just-In-Time. MANUPLAN gives the user insight into the effects of various reliabilities in addition to the usual design parameters of network models.

Sophistication is "Buried": As can be seen, MANUPLAN is based on some very new advances in analytic modelling. In fact, the software contains several complex and sophisticated algorithms. However, in keeping with our goals, every attempt has been made to insulate the user from the need to comprehend these algorithms: the natural and intuitive terminology, the simple interface, and the quick response allow the user to easily communicate the required data and just as easily understand the output reports. Much thought was given to making the translation process -- converting user inputs into the technical parameters required for the components of the models -- effective and accurate.

Training: While all attempts have been made to keep MANUPLAN easy to use, it is nevertheless a sophisticated tool based on complex mathematical theories. Like any tool, MANUPLAN can be misused just as easily as it can be used. In order to minimize this possibility, NDI provides a full day of training to the team of users whenever MANUPLAN is installed. This training covers not only the use of MANUPLAN, but also touches upon the assumptions and limitationsk of the model, as well as when it should not be used. (It is not necessary to go into the technical theory during this training, since these points are easily explained using qualitative criteria.) A good understanding of these issues has led to more effective use of MANUPLAN at user sites.

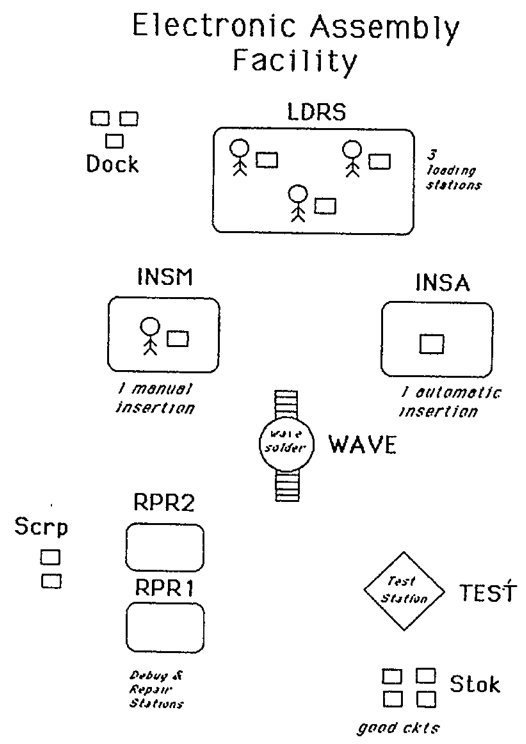
"What-If" Dials: The MANUPLAN input structure contains a number of parameters which can be thought of as "dials" which the user can manipulate to tune the performance of the system. This structure allows extremely fast exploration of "what-if" questions. As an example, consider this question: if the demand for Part 1 increased by 20% and for Part 2 by 30%, how much overtime would be required at each work center to keep WIP at current levels? To answer this sort of question, other analytic or simulation models would require many data changes and much work, but the examples below illustrate how easily this question is addresed using MANUPLAN.

3. BASIC CONCEPTS -- INPUTS and OUTPUTS

3.1 Inputs

As an example we shall consider a manufacturing facility for assembling electronic boards. MANUPLAN allows the manufacturing system to make several different **part-numbers** (every electronic board is a part, or part-number). Each part is manufactured via a **route**, or in some cases, via a sequence of **routes**. On a given route, a part will undergo a sequence of **operations**. Each operation is assigned to be done on one or more **equipment groups**. An equipment group is a collection of identical pieces of equipment, with identical capabilities. Transport systems can also be specified as equipment groups.

Figure 1:



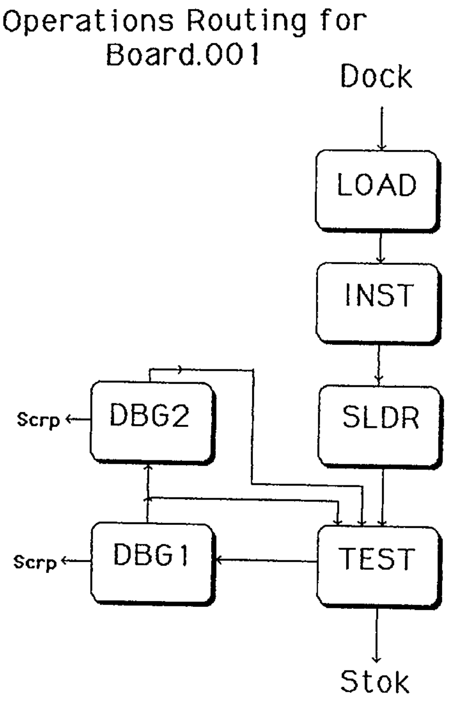
In the system described by Figure 1, these are the **equipment groups**:

LDRS - loading stations
INSA - automatic insertion of components
INSM - manual insertion
WAVE - wave solder
TEST - test station
RPR1 - debug/repair station no. 1
RPR2 - debug/repair station no. 2

The first part in the example system, (part-number BOARD.01), has an **annual demand** of 18,500 pieces. In the current design, it is decided to manufacture this part in **lot sizes** of 10. BOARD.01 is manufactured using a single route. MANUPLAN's treatment of routing data input helps the user to think in diagrammatic, flow-chart terms.

In Figure 2, the operation routing is indicated by the arrows. All material must flow into the system from DOCK, and exit the

Figure 2:



system into either STOK (stock) or SCRP (scrap).

Routing data include three items: an **operation**, the **next operation** or **operations**, and the **routing proportion between operations**. The input data for the route of BOARD.01 look like this:

* from * operatn	to operatn	proportion
dock	LOAD	1.000
LOAD	INST	1.000
INST	SLDR	1.000
TEST	stok	0.850
TEST	DBG1	0.150
DBG1	scrp	0.070
DBG1	TEST	0.750
DBG1	DBG2	0.180
DBG2	scrp	0.300
DBG2	TEST	0.700
stok		

Figure 2 indicates the route travelled by BOARD.01: the part goes from DOCK to the LOAD operation, from LOAD to INST (insert), from INST to SLDR (solder), continuing through all operations until either STOK or SCRP is reached.

The **routing proportion** is specified as 1.000 if only one possible next operation exists in the route. Note the several non-unity routing proportions at the TEST operation. If 85% of the boards are acceptable, on average, the routing proportion between TEST and STOK will be 0.8500. The rejected 15% are represented by a proportion of 0.1500 between TEST and DBG1. A certain proportion of boards (7%) sent to DBG1 will be beyond repair, and are sent from there to SCRP; 75% are thought to have been fixed and are returned to TEST; the remaining 18% are routed to DBG2. Similarly, from DBG2, 70% of the IC boards are returned to the TEST operation, with the remainder (30%) being scrapped.

The next set of input data is the **operation assignment**. It describes the assignment of operations to **equipment groups**. If an operation is always performed on only one equipment group, the proportion assigned is 1.000.

```
*oper   eqp-grp   proportn   time to   time per
*name    name     assigned   set up     piece
dock
LOAD   LDRS        1.000        0.0      10.0
INST   INSA        0.700       40.0       0.0
INST   INSM        0.300        0.0      25.0
SLDR   WAVE        1.000        0.0       4.5
TEST   TEST        1.000        7.0       2.0
DBG1   RPR1        1.000        0.0      32.0
DBG2   RPR2        1.000        0.0      60.0
stok
```

However, when an operation can be performed by several distinct equipment groups, then the proportion of parts operated upon by each group must be indicated. If, for example, components may be inserted into boards either automatically or manually, and if the automatic insertion machine has the capacity to handle all of BOARD.02 but only 70% of BOARD.01, then either an additional insertion machine, or a manual insertion station (a different equipment group), must be added to perform the operation. In our example, the operation INST for BOARD.01 is assigned to two equipment groups.

The time that it takes to set up an an item of equipment in an equipment group for a particular operation is the **setup time**. The time a workpiece needs to spend in an operation at a given equipment group is called the **operation time**, or **time-per-piece**. This measure depends on the part, the route, and the equipment group.

The **run title**, **minutes/day**, and **days/year** are indicated as follows:.

```
* run title (80 chars max)
Facility for Electronic Board Assembly
*
* minutes/day          days/year
*     nnnn                nnn
      960                 210
```

Next is the **equipment group data**.

```
  equip-grp  no. in        reliability (mins)
    name      group            mttf       mttr
    LDRS        3              9600        960
    INSA        1              4800         60
    INSM        1              4800         60
    WAVE       -1              6000        120
    TEST        1             10000        240
    RPR1        2             10000        240
    RPR2        1             10000        240
```

Specifying the **number in the group** has only one special case. If an equipment group's operation entails no queueing but only a measurable delay (a conveyer belt capable of handling as many pieces as are in the system at one time fits this description), the number of pieces of equipment in the group is specified as a -1.

The **reliability** of the equipment group is expressed as the **mean time to failure (mttf)** and the **mean time to repair (mttr)** in minutes. The specification is per piece of equipment.

Two quite interesting features of MANUPLAN are the **overtime factor** and the **speed factors (setup** and **run)**.

```
  equip-grp    overtime        speed-factor
    name        factor         setup      run
LDRS       ..     1.0          1.0        1.0
INSA       ..     1.0          1.0        1.0
INSM       ..     1.0          1.0        1.0
 ...       ..
```

These figures are set to 1.0 when the user desires a "straight" run of MANUPLAN. The various factors may be used like the volume dial on a stereo, but instead of altering the volume, in MANUPLAN the user can manipulate many of the system parameters.

To see the utility of these factors, consider the following case. Suppose an automatic insertion machine is available which can work at 1.5 times the speed of the currently proposed machine. One could change the process time for every operation of all parts on that machine, but changing every part data item would be extremely tedious. Moreover, the original data would no longer be available for comparison.

By instead manipulating the various factors, MANUPLAN allows the user to do rapid "what-if" calculations without changing the basic data. The overtime factor multiplies the number of minutes available at each equipment group. The setup/run factors speed up all setup/run operations performed at that equipment group.

Next is the part data for each part:

```
*    part           annual          lot
*   number          demand          size
   BOARD.01          18500           10
```

The part specification data include "what-if" capabilities similar to those found in the equipment group specification. Here, instead of overtime, we have a demand factor (its use is illustrated later).

```
* part    .. demand     speed-factor
* number  .. factor    setup       run
  BOARD.01 ..  1.2      1.0         1.0
```

The setup and run speed factors for part data affect all the operations for that part. In other words, suppose that a new material were introduced into a manufacturing system which required less processing time (perhaps the plastic part replacing metal could be cut twice as fast, or that a part has been redesigned with 20% fewer components). By adjusting the speed-factors, the effect of the new part on the system can be determined. Any number of combination of factors, both for equipment groups and parts, can be used together.

3.2 MANUPLAN Reports

This section explains the performance measures provided by MANUPLAN.

The first performance measure is the **production summary**. Here MANUPLAN informs the user whether or not the desired production can be achieved. If production can be achieved, the annual production goals are echoed, **work-in-process** (in pieces) and **flow times** (in days) are indicated for each part number, as well as the **total work-in-process**. The case where production cannot be achieved is described later.

The production rate will vary for each part type, since processing requirements differ for each part, so MANUPLAN gives a breakdown of the production rate by part.

```
*  production summary
*
*  Part     annual prodn.  flow time   work-in-
*  number   good   scrap    (days)     process
   BOARD.01  18500  404.8     2.0        249.8
   BOARD.02  25000  885.7     2.3        269.4

            total w.i.p. (pieces) = 293.1
```

Listed with each part number is an estimate of the wastage, or **scrap**, which must accompany the desired production. This scrap figure is useful: often individual operation yields are known, but the scrap figure indicates the total system yield when all operations are linked.

The **flow time** represents the average number of days required to complete all the processing for one lot of that part to go from DOCK to STOK. This includes all moving, waiting and processing encountered by a lot.

The last figure given in the production summary is the **total work-in-process**. This figure represents the average work-in-process inventory of that part in the whole system, given as a number of pieces.

Following the production summary is the **utilization summary**.

```
* Equip   no. in   utilizatn (%)    w.i.p.(lots)
* group   group   productn  repair    at group
   LDRS       3     74.1      9.1          4.2
   INSA       1     84.5      1.2          4.8
   INSM       1     70.3      1.2          2.0
   WAVE      -1      0.0      2.0          1.0
   RPR1       1     80.8      2.3          4.5
   RPR2       2     63.7      2.3          1.7
   TEST       1     83.7      2.3          5.0
```

A piece of equipment can be either in-use, idle, or under repair. For each equipment group, MANUPLAN gives the **average utilization** of each piece of equipment in that group for both **production** and **repair** (with the remaining proportion representing **idle-time**). These figures can help the user pinpoint the stress points in the system.

Similarly, bottlenecks can be identified by the **work-in-process** given for each equipment group. This is the average number of lots waiting or in process at the equipment group.

When there is a case of pure delay (the equipment group can handle as many pieces as necessary, with no queueing), the utilization will be indicated as 0.000; an example is a conveyer belt. The reason for the zero figure is that "utilization" is not well defined for such equipment. Both the repair proportion and the work-in-process are, however, correctly estimated in these cases.

3.3 Examples of MANUPLAN in Use

We now give examples to illustrate the various features of MANUPLAN, including the use of factors and the effects of changes in reliability.

When any single equipment group exceeds 95% utilization, it is assumed that production cannot be achieved. Above this percentage, the system becomes unstable to the extent that attempts to predict its behavior are not at all accurate. In such cases, the production summary merely indicates that the desired level cannot be achieved.

One example of the use of the demand factor follows. Suppose the demand for a part increases by 20% -- can the system handle it? If not, where will problems be encountered? A simple change (increasing the demand factor to 1.2 for board 1):

```
*  part       ..    demand   speed-factor
*  number     ..    factor   setup      run
   BOARD.01   ..     1.2      1.0        1.0
```

reveals, after a run of MANUPLAN, that production cannot be achieved. Both INSA and INSM are clearly over capacity:

```
*   Equipment    no. in   % of capacity req'd
*     group      group      productn    repair
      LDRS           3        87.8         9.1
      INSA           1       104.7         1.2
      INSM           1       101.3         1.2
```

```
     WAVE           -1           0.0         2.0
     TEST            1          93.6         2.3
     RPR1            2          75.1         2.3
     RPR2            1          91.4         2.3
```

As a second example, suppose that the reliability of an equipment group decreases. Perhaps INSA is a new type of machine and is not as reliable as was expected. The effect of reliability changes, expressed by decreasing the mttf and increasing the mttr, can be quickly determined. In the first example, mttf was 4800 and mttr was 60. The revised figures, as follows

```
*  eqp-grp  no. in      reliability
*   name     group       mttf       mttr
      ..
     INSA          1    600          120
      ..
```

have the following effect on the system:

```
*** equipment utilization summary

  the desired production can *not* be
  achieved
*
*  Equipment    no. in   % of capacity req'd
*    group      group    prodctn     repair
      ..
     INSA           1     84.5       16.7
      ..
```

Production cannot be achieved in this case, but not because any equipment group is over capacity in production; rather, it is because the combined production and repair figures for the breakdown-prone INSA machine result in a total utilization over 95%.

Returning to the first example, of a designer faced with a 20% increase in demand for BOARD.01, assume that he or she examines the utilizations to see where the stress falls. By adjusting the overtime factors for these equipment groups, the designer determines the minimum amount of overtime required to reach capacity:

```
  equip-grp          overtime
     name             factor
      LDRS       ..     1.1
      INSA       ..     1.2
      INSM       ..     1.2
      WAVE       ..     1.0
      TEST       ..     1.1
      RPR1       ..     1.0
      RPR2       ..     1.0
```

resulting in the following flow times and WIP as follows:

```
*  production summary
*
*  Part                  flow time   work-in-
*  number                (days)      process
   BOARD.01              2.0         249.8
   BOARD.02              2.3         269.4

                         total w.i.p.   519.2
```

MANUPLAN also predicts how the w.i.p. is distributed at each equipment group.

```
*   Equipment      w.i.p.
*     group        (lots)
       LDRS          6.3
       INSA          6.1
       INSM          4.6
       WAVE          1.2
       TEST          6.5
       RPR1          2.5
       RPR2         12.3
```

Looking at these figures, the designer notices the high WIP at RPR2, and investigates the effect of adding overtime at that equipment group, in addition to the overtime already specified.

```
*   Equipment      overtime
*     group        factor
      RPR2           1.2
```

This additional overtime gives rise to the following flow time and w.i.p. figures:

```
*  Part            flow time    work-in-
*  number           (days)      process
   BOARD.01        1.7          211.3
   BOARD.02        1.7          198.0

                   total w.i.p.    409.3
```

The w.i.p. at RPR2 has been reduced:

```
*  Equipment            w.i.p.
*    group              (lots)
      RPR2               3.0
```

The designer can now see that additional overtime (20% at RPR2) can save 110 boards of inventory, and result in a faster flow time. MANUPLAN helps the designer understand the tradeoffs between these various factors. The satisfaction for the designer, in obtaining immediate feedback on the effects of each change, as well as the importance for the manager, in receiving timely answers to urgent questions, make MANUPLAN a valuable addition to any manufacturing design team.

ACKNOWLEDGEMENT

Peter Wallace contributed to many of the concepts described here. We would also like to thank Rex Dean for editorial assistance in writing this paper.

APPENDIX: The Underlying Theory

MANUPLAN is based on some recent extensions to analytic modelling techniques. While the details of the implementation are quite complex, the basic concepts can be readily understood, and are outlined here.

Consider part i arriving at equipment k (see Fig. 3). Suppose we knew the (average) queue length of all parts of equipment k, seen by an arriving part of type i. Denote this by QA(i,j,k) for the "arrival" queue length of (each) part j, at equipment k, seen by an arriving part i. QA includes the part(s) in process. Let T(j,k) be the average operation time of part j at equipment k. Then the average time for part i to exit from k (its flow time through k) will be:

$$F(i,k) = T(i,k) + \sum_{j} QA(i,j,k)\ T(j,K) \tag{A.1}$$

Next, consider Little's law [14] applied at k. Let Q(j,k) denote the average queue length of part j at k, and let D(j,k) be the demand rate of part j at k. Then from [14],

$$Q(j,k) = D(j,k)\ F(j,k) \tag{A.2}$$

Finally, we need to estimate QA, and we do this by a transformation on Q. This transformation depends on the arrival process characteristics and the service characteristics, and requires making some approximations. Several approaches are available in the literature (e.g., see [15], or the survey [16]). The result is an estimate

$$QA(i,j,k) = \mathcal{F}(Q, i, \text{arrival/service processes}) \tag{A.3}$$

The details of $\mathcal{F}(.)$ for MANUPLAN have been developed at Network Dynamics.

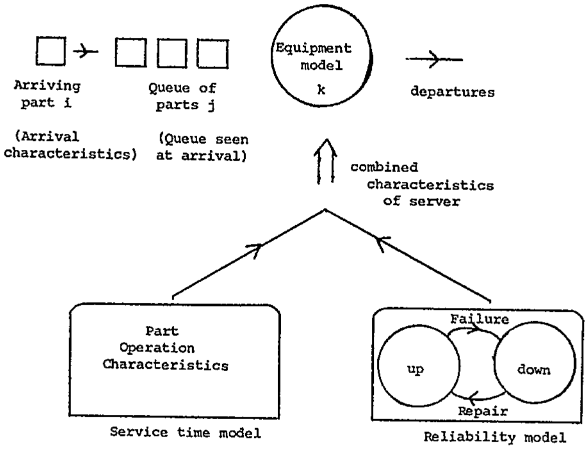
We now have enough equations in the sets (A.1)-(A.3) to solve for the unknowns Q(j,k) and F(j,k). This gives us the WIP and flow time for part j at k. We can use this basic step to build up WIP and flow time estimates for the whole system.

There are, however, a number of other issues to be addressed: i) Interconnection: the inputs to a work center are usually formed by the outputs of a number of work centers, with feedback loops in many cases. The arrival process to some equipment thus depends on the outputs of other equipment (and perhaps through a feedback loop, on itself). This requires iterative solutions of the equations in general. ii) Multiple-Servers: multiple items of equipment may be available at a work center. This reduces the waiting time of a piece, and (A.1) needs to be modified. iii) Fixture Constraints: for some operations, parts may need to be mounted on fixtures, and the number of available fixtures may be limited. In other cases, there may not be such a constraint. This is modelled by a mixed network, which allows both open (unconstrained) and closed (constrained) populations for different routes. (Incidentally, this is a unique feature of MANUPLAN, compared with previous manufacturing system models.) iv) Data conversion: part-data is specified in conventional manufacturing terms -- set up and run times, lot-sizes, routings, operation alternatives, etc., and MANUPLAN needs to convert these into basic characteristics of queueing processes.

All the above points have been addressed using well-known techniques (see bibliography and [16]), albeit with extensions developed at Network Dynamics to ensure fast and efficient solution.

As mentioned, MANUPLAN has the unique capability of modelling equipment reliabilities as well. This is done by using a reliability model to derive some server characteristics. These characteristics are then combined with the operation characteristics to come up with a model for the server as a whole (Figure 3).

Figure 3 Basic Server Model in MANUPLAN



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